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1 Unconventional filling dynamics of a pit crater

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3

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16

17 **Abstract**

18 The rise and fall of magma columns is a process commonly observed in volcanoes hosting lava
19 lakes and serves as proxy of magmatic reservoir pressure and warning for potential eruptions. This
20 dynamic process typically involves the filling and emptying of a “pit crater” - a cylindrical depression
21 usually formed by one or more collapses of a structure lying above an emptied surficial reservoir.
22 Between 2016 and 2020, the 300 m deep pit crater located within Nyamulagira volcano (Democratic
23 Republic of Congo) underwent an unusual filling dynamic. In May 2019 while filled to about 90%
24 the crater floor collapsed by 90 m within two months, followed by the rapid emergence of a sub-

25 circular solidified block overlooking the crater rim in less than 6 months. Using numerical
26 simulations of models based on thermal energy and constrained by multiparametric data, we
27 account for the incremental filling of the crater by successive intra-crateric lava flows and the
28 subsequent collapse of the crater floor. We further characterize this unconventional filling mode
29 based on thermal budget considerations.

30

31 **Keywords:** volcano; remote sensing; pit crater; lava lake; thermal model, thermal budget

32

33 1. Introduction

34 Pit craters are common features on basaltic volcanoes (Harris, 2009), defined as cylindrical
35 depressions with steeply inward dipping sides usually formed by one or more collapses of a
36 structure lying above an associated emptied surficial reservoir. Their evolution is closely related to
37 near surface magmatic activity (Walker, 1988). Pit craters may or may not be occupied by lava
38 lakes. Those lava lakes may be active, fed from depth and usually persistent over substantial period
39 of time. Their level within the crater vary in accordance to pressure changes at the base of a
40 convecting magmatic column (Burgi et al., 2020, 2002; Coppola et al., 2016a; Duffell et al., 2003;
41 Lev et al., 2019; Patrick et al., 2019; Valade et al., 2018). Inactive lava lakes are in turn accounted
42 for by lavas erupted from active vents inside or outside the pit crater, spreading intermittent lava
43 flows within it (Harris, 2009; Swanson et al., 1979). Termination of magma supply will cause the
44 entrapped lava layers to gradually cool and solidify.

45 While the dynamic of active (convective) lava lakes have been extensively modelled (e.g., Harris,
46 2008), the emplacement of inactive lava lakes still lack a dedicated model able to explain the
47 complex dynamics of filling, emptying and solidification operating within these structures (e.g.,
48 Harris, 2009). The two filling dynamics (active and inactive), may produce similar surface structures

49 making the recognition of one mechanism rather than another not trivial. However, the two
50 mechanisms are likely characterized by different ratio between the thermal energy radiated by the
51 lake surface, and the volumetric growth rate inside the pit crater. In fact, active lava lakes radiate
52 much more thermal energy than that contained in the lava that eventually accumulates on the
53 surface (Coppola et al., 2013). This is because the convective magma column allows the hot
54 magma to rise, degas and loose heat, before most of it is cycled back into the system (Burgi et al.,
55 2020, 2002). The extreme case is visible in stable, long-lived lava lakes that emit a considerable
56 amount of heat without increasing its volume (e.g. Erta Ale, Erebus, Nyiragongo during stable
57 phases, Harris et al., 1999). On the contrary, inactive lava lakes, being basically fed by an effusive
58 activity, are characterized by thermal emissions that are proportional to the volume of erupted lava
59 (Coppola et al., 2013; Harris and Baloga, 2009), without any additional contribution due to
60 convective processes.

61 In this study we report the evolution of a new lava lake which appeared inside a summit pit crater
62 of Nyamulagira (Democratic Republic of Congo) in 2014 (Fig. 1c). Ground and satellite
63 observations (see methodology) have made it possible to track the filling dynamic of the pit crater
64 by measuring the volume of lava accumulating inside, as well as the net discharge rate (Q_{out}) and
65 the volcanic radiant power associated to the surface activity (VRP). These observations highlight
66 the occurrence of distinct phases of rise of the pit-crater floor, that cannot be accounted exclusively
67 by one of the above-mentioned models, but rather by a transition from active to inactive filling
68 mechanism. Moreover, during the phase of inactive lava lake emplacement, we observe the
69 subsidence of the pit-crater floor, followed by the uplift of a solidified basaltic block whose dynamics

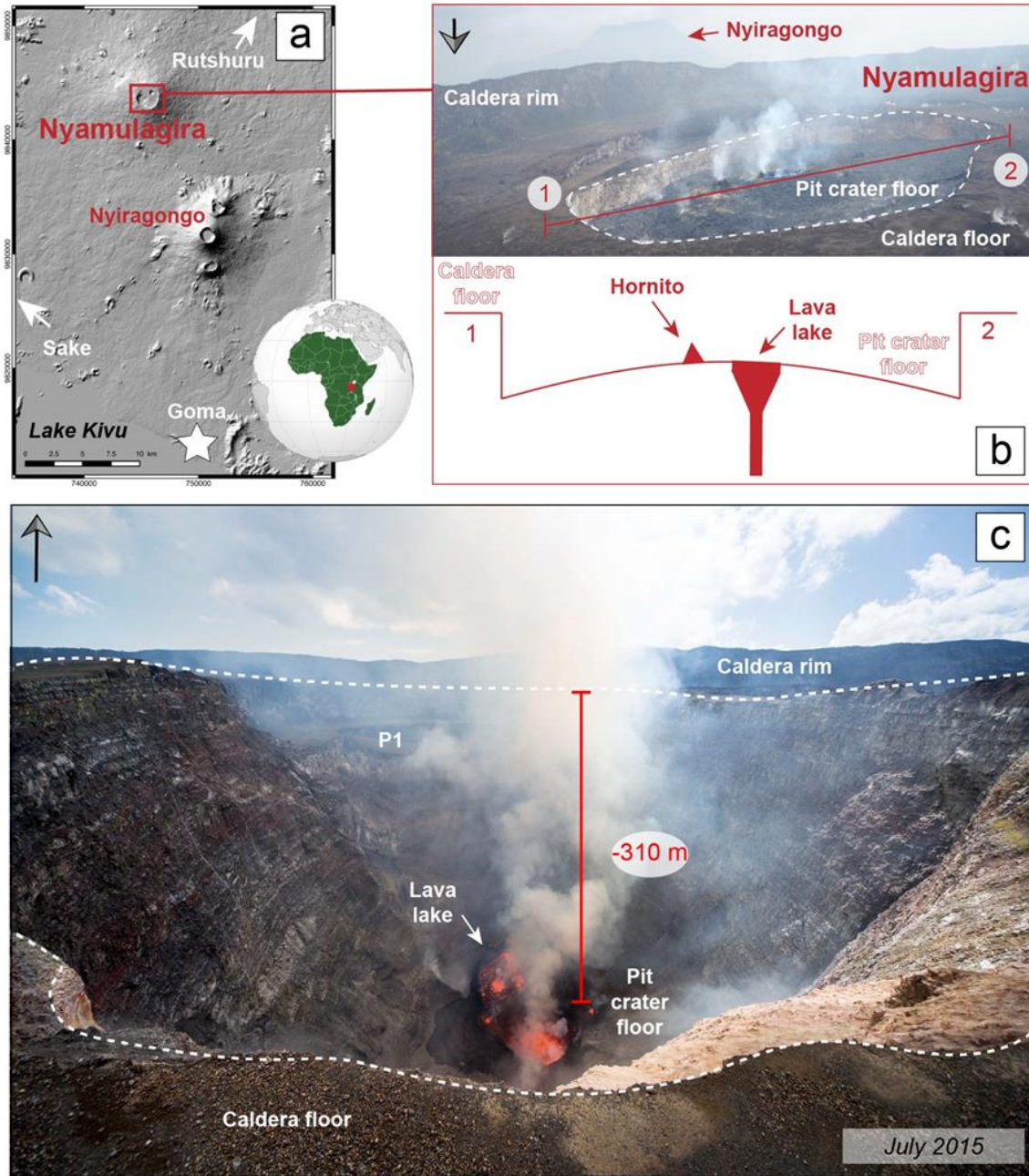
70 shares typical aspects of both the subsidence and resurgence of solid blocks observed in caldera-
71 forming eruptions.

72 We thus focus on the peculiar filling-emptying-filling dynamics characterizing the inactive lava lake
73 stage between 2016 and 2020, and we propose a thermal model (fed by remote-sensed data)
74 whereby successive intra-crater lava flows pile up at different rates to produce layers of lava with
75 different states of solidification. On this basis, our model is able to explain the complex pit-crater
76 evolution recently observed at Nyamulagira which include the unusual subsidence and block uplift,
77 rarely observed at mafic calderas (Galetto et al., 2019; Geist et al., 2006a).

78 **2. Nyamulagira setting**

79 Nyamulagira is the westernmost volcano of the Virunga Volcanic Province (Democratic Republic
80 of Congo - DRC) in the western branch of the East African Rift System (EARS) (Fig. 1a). It is a
81 predominantly mafic shield volcano with a 3058-m-high summit caldera, a diameter of more than 2
82 km, and one of the most active volcanoes of the EARS (Bluth and Carn, 2008). As many basaltic
83 shield volcanoes, Nyamulagira is mostly characterized by frequent flank eruptions, with a total of
84 40 occurrences from the summit crater and from its flanks over the last 120 years (Michellier et al.,
85 2020; Pouclet and Bram, 2021). The presence of a lava lake has also been documented in 1930-
86 1938 (Wadge and Burt, 2011) and its drainage in 1938 has led to the longest (more than 2 years)
87 and most voluminous ($>200 \times 10^6 \text{ m}^3$) historical eruptive event (Pouclet, 1975; Wadge and Burt,
88 2011), with lava flows rapidly reaching Lake Kivu located 25 km downstream. The very end of the
89 2011–2012 peripheral eruption was marked by a co-eruptive explosive collapse of a pit crater floor
90 in the caldera's north-eastern sector. After a period of 74 years (R. Hoier, 1939) a new lava lake
91 was firstly observed in 2014 (Campion, 2014; Coppola et al., 2016a; Smets et al., 2015, 2014),
92 occupying the bottom of this pit crater estimated between 400 and 500 m deep. This pit crater has

93 now almost (not always) lost its frequent use as a lava lake container and seems to represent the
94 central (superficial) part of Nyamulagira's plumbing system (Pouclet and Bram, 2021; Wauthier et
95 al., 2013).



96

97 **Fig. 1.** Setting of the pit crater. (a) Location of Nyamulagira and Nyiragongo (another active
98 volcano), and the City of Goma. Digital Elevation Model (DEM) computed from the Shuttle Radar
99 Topography Mission (SRTM, 2000) data extracted from USGS Earth Explorer. (b) Aerial image on
100 February 18, 2019 pointing out the morphology of the pit crater at Nyamulagira along with cross
101 section schematically illustrated (vertical scale exaggerated). At this time the pit crater was about
102 600 m long and 400 m wide and was almost completely filled. (c) The pit crater in July 2015.
103 Pictures from the authors.
104

105 **3. Methodology**

106 **3.1 Data Acquisition**

107 Periodic field surveys inside the Nyamulagira caldera were carried out between November 2014
108 and February 2020 with the support of the Observatoire Volcanologique de Goma (OVG) and the
109 MONUSCO (United Nations Organization Stabilization Mission in DRC). During each mission (from
110 a few hours to several days), a comprehensive series of field observations and measurements were
111 conducted to document the physical configuration of the active pit crater, using Laser Range Finder
112 Binoculars. These field campaigns were supplemented by helicopter observations performed by
113 MONUSCO whenever they could fly over this region. which made it possible to estimate the pit-
114 crater floor level at different states of its evolution with an accuracy of about 10% of the absolute
115 value.

116 These estimations were complemented by Sentinel-1 Synthetic-Aperture Radar (SAR) images
117 processed by the MOUNTS volcano monitoring system (Valade et al., 2019) ([www.mounts-
118 project.com](http://www.mounts-project.com)) to measure both the pit-crater depth evolution and the caldera deformation, from
119 January 2018 to June 2020. Depth is calculated from the intensity image, by measuring the length
120 of the shadow casted by the pit crater walls in radar geometry, and multiplying it by the cosine of
121 the radar incidence angle (Wadge et al., 2011). The method has successfully been applied to track
122 lava lake level variations (Barrière et al., 2018; Moore et al., 2019), and here provides continuous

123 variations of the pit-crater floor, which are validated by sporadic field measurements. Deformation
124 is calculated from standard differential SAR interferometry analysis (D-InSAR), with interferograms
125 computed with the shortest temporal baseline, i.e., between two consecutive acquisitions (typically
126 6-day interval on the ascending track, and 12-days interval on the descending track). Unwrapping
127 of the interferograms was done with SNAPHU to recover ground deformation in the radar line-of-
128 sight (LOS) in meters. The ground and satellite data relating to the depth of the pit crater were used
129 to calculate the volume of lava accumulating inside the pit crater (assuming an inverted truncated
130 cone geometry with $r_{min}= 113$ m and $r_{max}= 250$ m; Fig. 2a). Volumetric estimates have been finally
131 used to calculate growth rate (Q_{out}) for each analyzed period (Fig. 2b).

132 Thermal emissions have been detected using infrared data provided by the moderate resolution
133 imaging spectroradiometer (MODIS), compiled within the Middle InfraRed Observation of Volcanic
134 Activity (MIROVA) system (Coppola et al., 2016b; www.mirovaweb.it) to facilitate their analysis and
135 determine the volcanic radiative power (VRP; Fig. 2c). The MODIS data were supported by the
136 images acquired from the Copernicus Sentinel 2 sensors (resolution of 20 m in the short-wave
137 infrared - SWIR bands), which made it possible to identify in greater spatial detail the high
138 temperature areas at the origin of the measured heat flux.

139 **4. Observations and measurements**

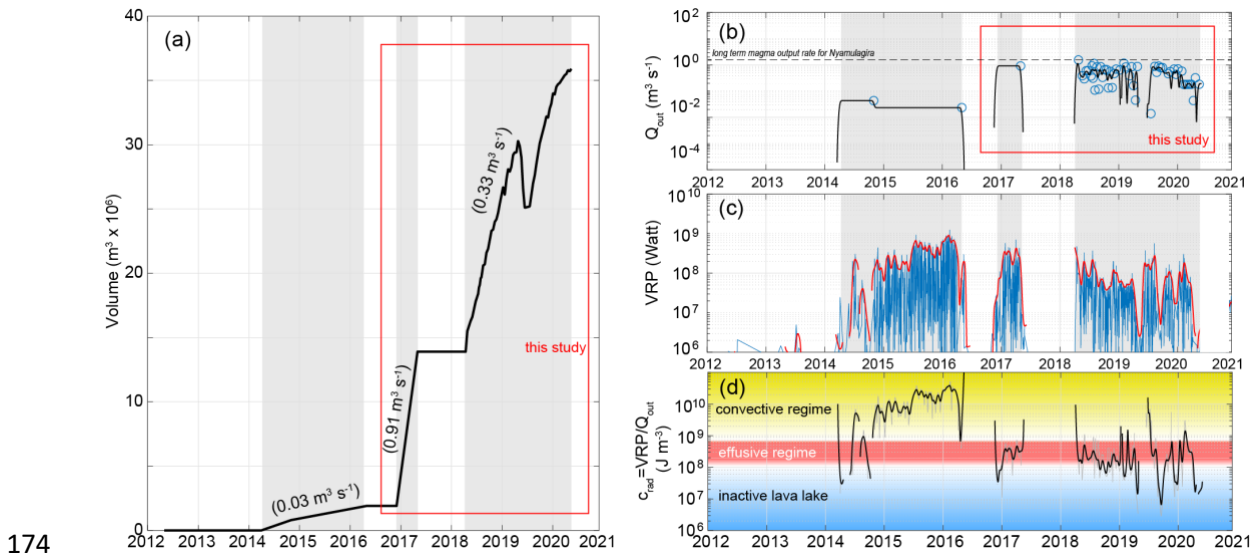
140 **4.1 Pit-crater filling dynamic between 2014 and 2020**

141 First observations of a lava lake inside the summit pit-crater of Nyamulagira date back to mid-2014
142 (Coppola et al., 2016b) when visual observations confirmed the presence of fresh magma (~50 m
143 diameter) lava lake at the bottom of the pit-crater (~500 m depth). In July 2015, the lava lake
144 displayed an elliptical shape, 150 m long and 100 m wide, and was located at a depth of 310 m

145 below the crater rim (Fig. 1c). This initial phase of activity (volume less than $2 \times 10^6 \text{ m}^3$) was followed
146 by a period without any evidence of lava lake activity (Supp. Fig. S1a) until December 2016, when
147 the pit crater started to be filled by fresh lava. The new vigorous filling phase led the pit crater floor
148 to rise at a depth of 160 m below the crater rim, with a diameter of $\sim 190 \text{ m}$ and a volume of
149 $\sim 14 \times 10^6 \text{ m}^3$ by May 2017 (Supp. Fig. S1b). A new phase of rest occurred between June 2017 and
150 May 2018 when the third filling phase started (see next section). Overall, the volume of lava
151 accumulated in the pit-crater from April 2014 to April 2020 amounts to approximately $37 \times 10^6 \text{ m}^3$
152 with an average magma output rate of $0.18 \text{ m}^3/\text{s}$ (Fig. 2a). This volume of lava accounts for only
153 12% of the long-term magma output rate of Nyamulagira between 1980 and 2012 ($\sim 1.5 \text{ m}^3/\text{s}$;
154 Coppola et al., 2016a; Fig. 2b).

155 The three main phases of lava lake growth are well highlighted by the cumulative volume trend as
156 well as by the evolution of the lava discharge rate (Q_{out}) and by the VRP (Fig. 2). As anticipated in
157 the introduction the ratio between thermal flux (VRP) and volumetric growth rate (Q_{out}), hereby
158 defined as $c_{rad} = \text{VRP}/Q_{out}$ (Coppola et al., 2013) is a parameter representing the amount of heat
159 radiated into the atmosphere for each cubic meter of lava erupted or accumulated inside the crater
160 (Fig. 2d). c_{rad} outlines how the three phases represented in Fig. 2a, were characterized by
161 markedly different values (Fig. 2d), likely associated to distinct mechanism of lava lake formation
162 (see Introduction). The first phase (May 2014 to May 2016) was characterized by $c_{rad} > 10^9 \text{ J/m}^3$
163 (Fig. 2d), a value much higher than the one typically measured during the flank lava-flow-forming
164 eruption of Nyamulagira $2\text{-}5 \times 10^8 \text{ J/m}^3$ (Coppola and Cigolini, 2013; red field in Fig. 2d). We ascribe
165 this phase to the development of an active lava lake, whereby the excess of radiation is associated
166 to the convective circulation of magma at shallow depth. Conversely the second (December 2016
167 to May 2017) and third (April 2018 to April 2020) filling phases were characterized by a c_{rad} similar
168 to, if not even smaller than, the typical value characterizing the effusive regime. This is likely due

169 to the absence of magma convection and to the limited surface area of lava flows confined within
 170 the pit, the thickness of which is controlled by geometric, rather than rheological, factors (Harris
 171 and Baloga, 2009). Accordingly, we ascribe these two phases to the intermittent growth of an
 172 inactive lava lake (blue field in Fig. 2d) whose detailed morphological evolution is described in the
 173 next section and modelled in section 5.



174
 175 **Fig. 2.** (a) Cumulative volume of lava emplaced inside the summit crater of Nyamulagira between
 176 the first appearance of a lava lake, in 2014 (Coppola et al., 2016a) and mid-2020. Three main
 177 growth phases (grey fields) are defined by the respective time-averaged lava discharge rate (in
 178 parenthesis). (b) The lava output rate (Q_{out}) associated to each phase is compared to the long-
 179 term magma output rate ($1.5 \text{ m}^3/\text{s}$) that characterized Nyamulagira effusive activity between 1980-
 180 2012 (Aoki et al., 1985; Coppola et al., 2016a). (c) Volcanic Radiative Power (VRP) associated to
 181 the three phases, as measured by the MIROVA system. (d) ratio between the radiant and

182 volumetric flux ($c_{rad}=VRP/Q_{out}$) throughout the analyzed period. Yellow and blue colored fields
183 refer to active and inactive lava lake mechanisms, respectively.

184 **4.2 Pit-crater activity between 2018-2020**

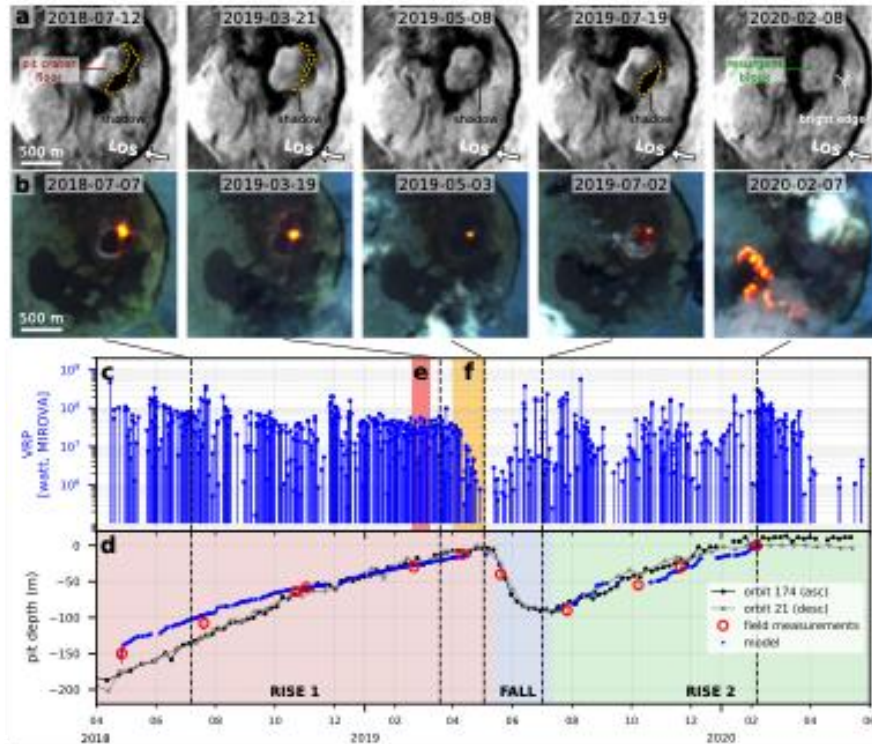
185 The third phase of growth (2018-2020), on which we focus in this study, was characterized by a
186 complex dynamic which we subdivided into three stages.

187 *4.2.1 Filling of the pit-crater (May 2018 – April 2019: Rise 1 phase)*

188 In May 2018 MIROVA thermal anomalies were suddenly detected after a nearly 1-year hiatus, and
189 the level of the pit-crater floor began to rise at a steady rate, as evidenced by the Sentinel-1 SAR
190 analysis (Fig. 3a,d) and field measurements.

191 Ground observations in July and November 2018 put in evidence intra-crateric lava flows taking
192 their origin either from a small lava lake (when present) or from hornitos (Fig. 4a,b & Supp. Fig.
193 S2). In February 2019, the small lava lake was located at the top of a convex surface that occupied
194 the whole crater and dominated the bottom of the cliffs from a height of about 15 m (Figs. 1b & 4b).

195 At this time, lava flows could be observed at the base of the pit-crater cliffs and occurred nearly
 196 continuously during our 5-day stay (Fig. 4b).



197

198 **Fig. 3.** Multiparametric data analysis. (a) Sentinel-1 SAR acquired in descending orbit (orbit 21,
 199 line-of-sight LOS represented by white arrow), geocoded and speckle-filtered. The variations of the
 200 shadow casted inside the pit crater (dashed yellow lines) highlight the variations of the crater depth.
 201 (b) Sentinel-2 SWIR bands 12-11-8A. (c) Volcanic Radiative Power (VRP) measured from MODIS
 202 TIR images (processed by MIROVA). (d) Pit crater depth estimated from field measurements (red
 203 markers), Sentinel-1 SAR images with ascending and descending orbits in black and gray
 204 respectively (processed by MOUNTS), and lava layers thickness modeling (blue line). The 3 phases
 205 corresponding to the filling (Rise 1), emptying (Fall), and re-filling (Rise 2) of the pit-crater are
 206 highlighted in red, blue and green respectively (as in Figure 4). (e) Timespan indicating when
 207 deformation was measured by InSAR following a dyke intrusion under the caldera (Supp. Fig. S3).
 208 (f) Timespan indicating a period when the thermal radiation decreased significantly, evidenced by
 209 a drop in the VRP values and a decrease of the active lava lake dimensions.

210

211 From January 2019 to June 2019, tectonic seismicity around the Nyamulagira area shallower than
 212 20 km was recorded by the seismic network of the Goma Volcanology Observatory (GVO). Many

213 inhabitants have reported experiencing earthquakes in the North (mostly from the City of Rutchuru,
214 located 35 km from Nyamulagira), and South of Nyamulagira, particularly in the lake Kivu area,
215 including the Goma City, with magnitudes up to 4.5. In February 2019, deformation inside the crater
216 was detected in three distinct interferograms, spanning from February 13 to March 9, 2019 (Fig.
217 3e). The InSAR deformation pattern suggests that a dyke firstly propagated from the pit crater
218 towards the South-East and accumulated under the most eastern-side of the caldera floor (Supp.
219 Fig. S3). No lava emissions were associated with this deformation episode, which resulted in a
220 maximum deformation in the radar line-of-sight of 8.4 cm. Shortly afterwards, the thermal activity
221 within the crater dropped significantly from April 12, 2019 to early May 2019 (Fig. 3f), as testified
222 by the decrease in VRP detections. Notably, the decrease in the lava lake size (which was 50 m
223 long and 30 m wide at the end of February 2019), and the disappearance of lava flows surrounding
224 the crater floor, visible already in July 2018 (Fig. 3b) were not accompanied by the subsidence of
225 the pit-crater floor but rather, by a slow upward rise (Fig. 3d).

226 *4.2.2 Subsidence of the pit-crater (May 2019 – June 2019: Fall phase)*

227 A radical change in the crater activity occurred in May 2019 with a large subsidence of the pit-crater
228 floor lasting 2 months (Fig. 3d, "Fall" phase). The first ground-based observation of this
229 phenomenon dates back to May 2019 with a floor subsiding by about 10 m with respect to its level
230 two months before. While no direct observations were reported, both MONUSCO, which makes
231 regular reconnaissance flights in this area, and local inhabitants reported rumbling and smoke from
232 inside the crater, that could correspond to the floor's detachment. MONUSCO also reported that a
233 camp inhabited for more than 10 years by a rebel group on the southern upper flank of the volcano
234 was suddenly abandoned in the second half of May 2019. However, as the closest seismic station
235 is 25 km away, the event did not yield discernible seismic signals, with the exception of two long-

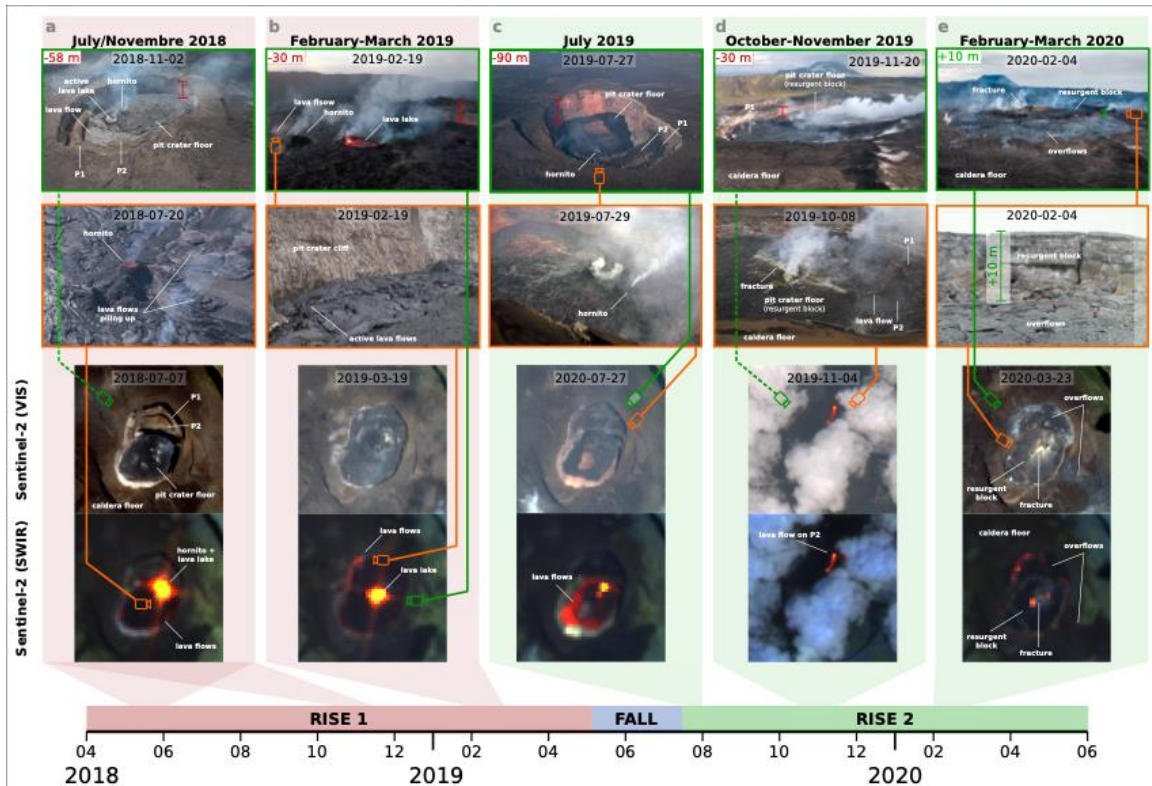
236 period (LP) seismic swarms in May 8-9, 2019 and in May 16-19, 2019, which could be linked to the
237 first phases of the sinking of the pit-crater floor.

238 This subsidence reached -90 m at the end of July 2019 (Fig. 4c), representing a loss of a volume
239 of lava of about $8 \times 10^6 \text{ m}^3$. No fractures of the pit-crater floor nor at its surroundings or outside the
240 crater on its flanks were observed, as it usually occurs during caldera collapses at basaltic shield
241 volcanoes (Derrien et al., 2020; Neal et al., 2019). The morphology of the pit crater floor with the
242 hornito in its center stayed surprisingly intact and kept degassing (Figure 4c). Two platforms located
243 in the northern part of the pit crater (P1 and P2, Fig. 1c), which had been covered with a lava layer
244 estimated to be 35 m thick during the filling of the pit crater in 2018, were cleared and became
245 partly visible again (Fig. 4c).

246 *4.2.3 Re-filling of the pit-crater and uplift of a solidified block (July 2019 – February 2020: Rise 2*
247 *phase)*

248 Following the subsidence phase, the pit-crater floor resumed rising at the end of July 2019 (Rise 2
249 phase), with the emplacement of lava flows at the bottom of the pit (Fig. 4c). Shortly after, the
250 bottom of the pit-crater appeared as a sub-circular 290 m x 390 m solidified block as attested by
251 the development of a large fracture (Fig. 4d & Supp. Fig. S4). This solidified block stayed intact
252 throughout this re-filling phase (fracture still visible in the 2020-03-03 satellite image, Fig. 4e &
253 Supp. Fig. S5a), suggesting that the block was being pushed from below similar to a piston-
254 mechanism, with an uplift rate in the order of cm per hour. In February 2020, the pit crater was
255 completely filled and lava was overflowing from its periphery onto the main caldera floor (Fig. 4e &
256 Supp. Fig. S5). At this time, the emergent solidified block protruded about 10 m above the caldera
257 floor (Fig. 4e). This protruded topography was also observable on Sentinel-1 SAR images, as the
258 pit-crater edge no longer appeared as a dark shadow (i.e. negative topography), but rather as a

259 thin bright edge, indicating the reflection of the radar electromagnetic wave onto a positive
 260 topography (Fig. 3a).



261
 262 **Fig. 4.** Evolution of the pit crater morphology from April 2018 to June 2020 based on photographs
 263 and satellite images (Sentinel-2, optical and SWIR band combinations). The 3 phases
 264 corresponding to the pit-crater filling (Rise 1), emptying (Fall), and re-filling (Rise 2) are respectively
 265 represented in red, blue, and green (as in Fig. 3). Pictures from the authors.
 266

267 5 Numerical Models

268 Based on the above-described multiparametric data, modeling was used to explain (i) the filling of
 269 the pit crater, (ii) the subsidence that followed without evidence of brittle fracturing, (iii) the
 270 emergence of a solidified block, and (iv) the state of crystallization of the successive layers based
 271 on a thermal model. Note that only the period preceding subsidence (April 2016 to April 2019, Supp.

272 Fig. S1) is considered for the thermal model, as “rise 2” phase involves a piston effect not fully
273 accountable by a thermal model.

274 **5.1 Lava layer thickness**

275 We model the filling of the Nyamulagira crater from April 2016 to February 2020 not as a rising lava
276 lake, but rather as the stacking of a succession of distinct lava flows detected remotely by the
277 MIROVA system. We apply the following relation between the radiative energy VRE and the
278 erupted volume V (Coppola et al., 2013),

$$279 \quad c_{rad} = \frac{VRE \gamma}{V} \quad (1)$$

280 where γ is a correction factor (set to 1.3) for compensating the thermal energy attenuation due to
281 the presence of clouds (frequent in this region), and c_{rad} is the radiant density, which characterizes
282 several properties of the lava emplacement, such as insulation, rheological and topographic
283 conditions. The particular geological context of these flow units (lava flows confined in a deep
284 crater) implies that, for a fixed effusion rate, these intra-crater lava flows will have a smaller surface
285 area than equivalent lava flows that are emplaced along the flank of the volcano (free to expand).
286 For the case of caldera confined lava emplacement, the thickness of the lava layers at day n may
287 be approximated by $H_n = V_n/(\pi r^2)$, with r the average pit crater radius. From equation (1), which
288 takes into account all radiative sources, including the presence of a small lava lake, we can express
289 the layer's thickness H_n as

$$290 \quad H_n = \frac{VRE_n H_{tot}}{VRE} \quad (2)$$

291 with H_{tot} being the total lava flow thickness, and VRE_n corresponding to the radiative energy
292 calculated for each specific day n . To avoid unrealistic lava flows, a thickness smaller than 10 cm

293 is discarded. Consequently, the time separating two lava flows is determined by the occurrence of
294 layers thicker than this threshold value.

295 **5.2 Collapsing conditions**

296 According to visual observations performed in July 2019 (Fig. 4c), the floor's detachment has
297 occurred along a pit-crater segment with sub-vertical cliffs. We thus model it as a vertical piston
298 whose load is balanced by friction at the wall surrounding it. Also, the condition for a solid portion
299 of height H_s in contact with pit-crater walls to collapse is satisfied when the vertical load (F_v) (Duputel
300 and Rivera, 2019; Kumagai, 2001)

$$301 \quad F_v = \frac{\pi D^2 H_s \rho g}{4} \quad (3)$$

302 with D the average pit-crater diameter, ρ the density of degassed magma, and g the gravity
303 acceleration, exceeds a critical shear force (F_s) given by (Roche and Druitt, 2001)

$$304 \quad F_s = \tau_c \pi H_s D, \quad (4)$$

305 where τ_c is the critical shear stress for rupture, taken to follow the Coulomb fracture criterion
306 (Nicholson, 1994),

$$307 \quad \tau_c = \tau_0 + \mu \frac{\nu}{1-\nu} \frac{\rho g H_s}{2}, \quad (5)$$

308 with ν the Poisson's ratio and μ the sliding friction. Because the pit crater was filled by successive
309 lava layers, and that lava may be oozing at the edges and thus lubricating some contact points,
310 cohesion τ_0 is estimated to be 1-2 orders of magnitude lower than the value for intact basalt
311 (Schultz, 1995). To be conservative, we set $\tau_0 = 1 \times 10^6$ Pa. Combining the last three equations,
312 the collapse condition $F_v > F_s$ is verified for

313
$$H_s < \frac{1-\nu}{\mu\nu} \left(\frac{D}{2} - \frac{2\tau_0}{\rho g} \right) \quad (6)$$

314 With the parameters reported in Table 1, we estimate a total solid layer height $H_s < 423$ m. Later
 315 in Section 4.2 we show that the solid layers are all much smaller than this value, which indicates
 316 that the collapsing condition is always satisfied once the underlying pressure drops.

317 **5.3 Heat equation**

318 Based on ground observations (Fig. 4 & Supp. Fig. S2), we take for granted that magma erupts by
 319 successive lava flows, the initial one with thickness H_1 at liquidus temperature T_{liq} . By heat radiation
 320 and convection within the surrounding atmosphere T_{atm} , cooling of the lava surface starts and
 321 proceeds by conduction toward the lava interior, with latent heat released inside the lava layers
 322 due to crystallization. A new lava flow covers the previous layer with thickness H_2 , and the process
 323 repeats until the crater is filled. The layer thickness H_n (equation 2) and the lava flows' occurrence
 324 time t_n are both evaluated based on the radiant density estimated from MIROVA data.

325 Temperature and melt fraction of the lava layers are computed using the finite difference expression
 326 of the heat equation. Given the horizontal spatial extent of the pit crater (several hundreds of
 327 meters) and duration of the considered period, we assume that the horizontal heat loss at the crater
 328 walls does not affect the vertical temperature distribution, and thus a one-dimensional model can
 329 be applied. This assumption is at least reasonable for the central part of the crater under study. To
 330 calculate the temporal and spatial evolution of temperature $T(X, t)$ of this central part that
 331 experiences repeated accumulation of lava flows, we apply the heat equation, derived by combining
 332 the conservation of energy and Fourier's law

333
$$k \frac{\partial^2 T}{\partial X^2} = \rho c_p \frac{\partial T}{\partial t} - \rho L \frac{\partial f_c}{\partial t} \quad (7)$$

334 where (see Table 1) f_c is melt fraction (which depends on temperature), k is thermal conductivity,
 335 ρ is the density, c_p is specific heat capacity, L is latent heat, t is time, and X is vertical distance,
 336 which increases after each lava flow.

337 To best match available data on the rheology of Nyamulagira's lavas (Morrison et al., 2020),
 338 variation of the crystallinity with temperature T is approximated by a nonlinear function,

$$339 \quad f_c = a + b \sinh\left(c \frac{T - T_{sol}}{T_{liq} - T_{sol}} + d\right) \quad (8)$$

340 with T_{sol} the solidus temperature, which for many magmas is observed to correspond to $T_{liq} - 200$
 341 (Marsh, 1981; Wright and Marsh, 2016), and T_{liq} is set to 1260 °C (Morrison et al., 2020). This
 342 function yields slow crystallization within the first 80-100 °C subliquidus, and then changes regime
 343 with a fast increase in the rate of crystallization. While the absolute temperature of this interval
 344 shifts to lower temperatures with decreasing oxygen fugacity, the width of this temperature interval
 345 remains similar (Kolzenburg et al., 2020, 2018a). Substituting this definition for f_c in equation (7),
 346 we get

$$347 \quad \frac{\partial^2 T}{\partial X^2} = \frac{\partial^2 T}{\partial X^2} = \frac{\rho}{k} \left[c_p - \frac{L b c}{T_{liq} - T_{sol}} \cosh\left(c \frac{T - T_{sol}}{T_{liq} - T_{sol}} + d\right) \right] \frac{\partial T}{\partial t} \quad (9)$$

348 with parameters a , b , c and d in Table 1. With the chosen parameters, the “cut-off” temperature
 349 where crystallization exponentially increases (Kolzenburg et al., 2016) is at 1180 °C. The heat flux
 350 from the lava surface ($X = 0$) is described by a boundary condition, which we take

$$351 \quad \sigma \varepsilon (T^4 - T_{atm}^4) - k \frac{\partial T}{\partial x} = 0 \quad (10)$$

352 where the first term stands for the radiant heat flux, with σ the Stefan-Boltzmann constant and ε
 353 the emissivity of the lava surface, and the second term stands for heat transfer by conduction. It
 354 must be noted that we neglected heat transfer by natural convection in this equation as heat lost

355 by radiant heat flux is several orders of magnitude larger for the range of considered temperatures.
356 On the other hand, latent heat, liberated as lava solidifies, has a significant effect and provides a
357 large quantity of energy per unit mass that delays cooling.

358 To keep computation time reasonable, equations (9) and (10) were discretized on a spatial mesh
359 of 2.5 cm (the thinnest lava flow being 10 cm) and time increment fixed to 8 minutes. These settings
360 verify the mesh Fourier number criterion (Smith et al., 1985): for the considered heat equation this
361 criterion is given by $F = \frac{k}{\rho c_p} \Delta t / \Delta x^2$, which yields 0.49, verifying the stability condition $F < 0.5$. At
362 the occurrence of each lava flow, whose time of occurrence and thickness (see above) were derived
363 from the MIROVA data, the equation is reinitialized with new initial and boundary conditions, which
364 corresponds to instantaneously emplaced lava.

365 **Table 1 HERE.** Physical properties and parameters employed in the model.

366 **6 A stratified pit crater highlighted by numerical modeling**

367 The numerical solutions of the thermal model (vertical thermal profile) during the April 2016 - April
368 2019 period, reveal that just before the subsidence occurred in May-June 2019, the pit crater
369 consisted of an alternation of molten and solidified layers (Fig. 5b). Of the 290 m of lava piled up
370 during this period, about 160 m were solidified (cf. S1 to S5 on Fig. 5b) and 130 m were in a molten
371 state (cf. M1-M4 on Fig. 5b). The preservation of molten layers results mainly from the effect of the
372 latent heat generated during the cooling and solidification of other layers. Without this effect, almost
373 the entire pit crater would be solidified (Supp. Fig. S6). We argue that molten layers interspersed
374 between solid layers promote the collapse of the crater and accelerate the phenomenon (by
375 draining the molten layers – Fig. 5c). On contrary, the displacement of a 300 m rock thickness will
376 generate much more friction against the wall. While being conservative in the values of equation 6,

377 a thickness of 300 m is closer to the limit value (423 m), which might potentially be overvalued.

378 Moving thinner solid layers more easily meets the dropout condition.

379 The layer thickness evolution (described by equation 2 and inferred from MIROVA) closely fits the

380 field and satellite observations (Fig. 3b & Supp. Fig. S7) although the 2-3 m individual layers (middle

381 panel of Fig. 4e) and Supplementary Figure S4a cannot be resolved through the heat equation

382 solutions (e.g., Fig. 5b). This would have required the inclusion of layer boundary formation

383 mechanisms and intra-layer vertical variations (grain size, mineral compositions, textures, etc.

384 present in the layers) in the model that involve a wide variety of factors (Naslund and McBirney,

385 1996), which was not the focus of this study.

386 Because thermal parameters are rarely provided for specific volcanoes, and Nyamulagira is not an

387 exception, a sensitivity analysis was used to confirm the consistency of the results obtained (Table

388 1). No appreciable effect on the distribution of the solid layers in the stacked column have been

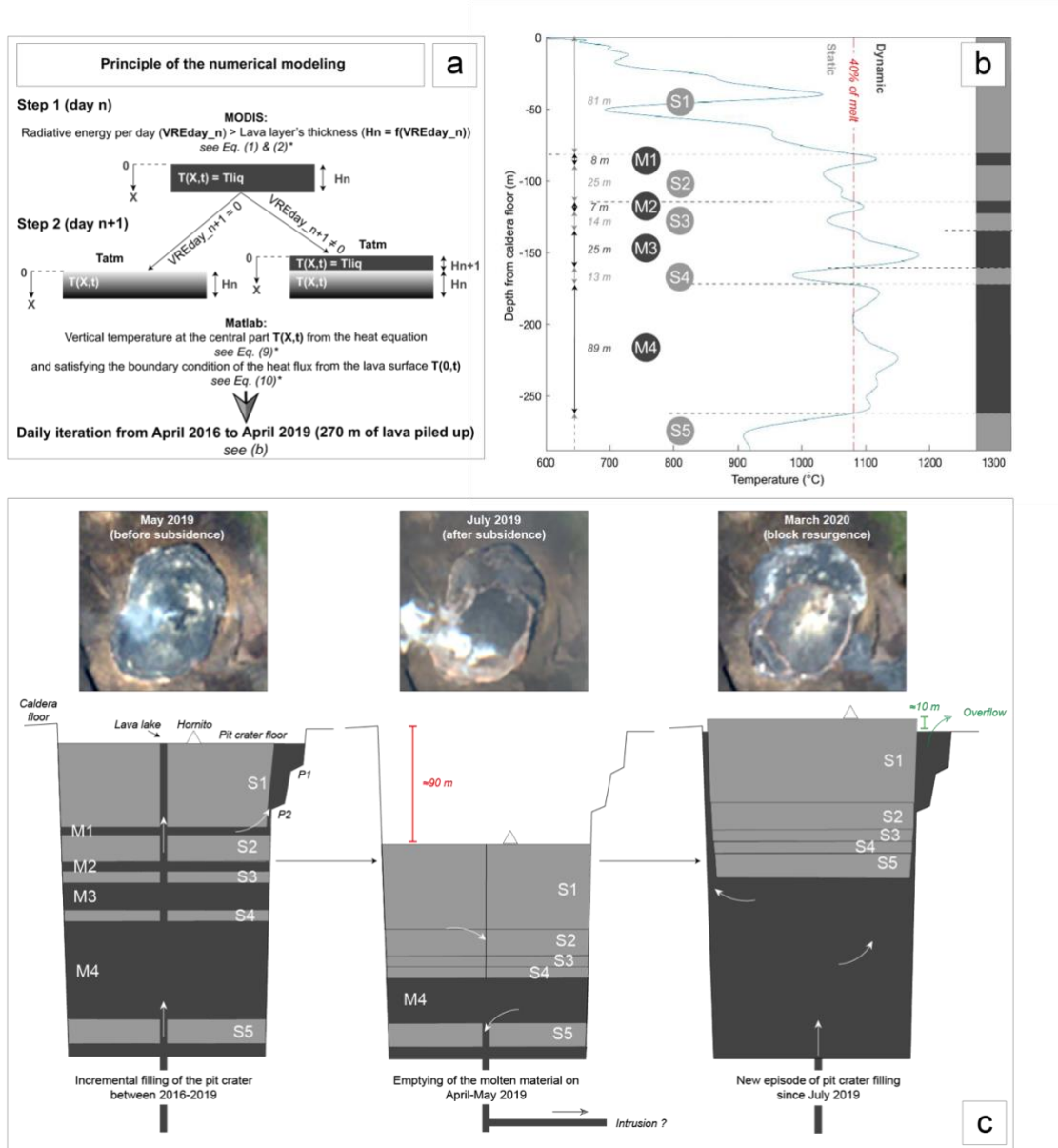
389 observed (Supp. Fig. S8), and the predominant variables turn out to be the timing and thickness of

390 the lava flow, both derived from MIROVA data. A similar observation has been reported for

391 incremental intrusions in sills in which the rate of basalt emplacement (represented here by the

392 timing and thickness of the lava flows) is an important variable in determining melt fraction (Annen,

393 2011; Jackson et al., 2018).



394

395 **Fig. 5.** Thermal modelling with the resulting collapse and emergence of the solid block scenario.
 396 (a) Description of the main principles used in numerical modeling. Equations (*) are described in
 397 Section 5. (b) Result of the numerical modeling (temperature profile) performed between April 2016
 398 and April 2019 (about 1000 days) to simulate the state (S: solid vs. M: molten layers) of the pit
 399 crater filled by 290 m of lava before its subsidence. The dashed red line indicates 40% melt fraction
 400 (below this line the lava is supposed to be static and above it flowing). (c) Interpretative scheme
 401 (not at scale) of the evolution of the pit crater before and after the subsidence (May 2019 - March
 402 2020) together with Sentinel-2 images.

403 **7 Discussion**

404 The morphology of the pit crater and filling mode since April 2016 have led to the layering of lava
405 with different states of solidification. The numerical solution of the thermal model (Fig. 5) shows
406 that before the subsidence of May 2019 (i) a large part of the pit crater (~130 m) was filled with
407 molten lava; (ii) the first 80 m upper segment of the pit crater is mostly solid, with a melt fraction
408 smaller than 40%, and is thus too viscous to flow (Annen, 2011; Kolzenburg et al., 2018b; Lamy-
409 Chappuis et al., 2020; Lejeune and Richet, 1995; Marsh, 1981; Sparks et al., 2019); (iii) under this
410 solid crust reside several molten lava layers, the largest one being over 90 m thick, interspaced by
411 solidified layers up to 25 m thick (Fig. 5b). We now discuss how this layer structure impacts the
412 subsidence of the pit-crater (May – June 2019) and the following uplift of a solidified block (July
413 2019 - February 2020).

414 **7.1 Subsidence and emergence mechanisms**

415 Subsidence of the crater floor, which started in May 2019 and lasted 2 months (Fig. 3d), is most
416 probably associated with lava draining from the shallow magmatic system. Although the origin of
417 such draining is still unclear and outside the scope of this study, it is worth noting that this
418 subsidence was preceded, 6 weeks before (in March 2019), by a small intrusion evidenced by
419 InSAR (originating from the pit-crater and extending under the caldera floor, Supp. Fig. S3),
420 concomitant to recorded tectonic earthquakes. Nevertheless, the intrusive episode was followed by
421 a month-long reduction of the thermal flux (Figs. 2c & 3c) possibly indicating a break in the
422 magmatic supply or a partial drainage of the magma column caused by the intrusion below the
423 caldera floor. It should be noted that this decrease of magma supply to the surface did not cause
424 the immediate collapse of the crater which began to subside only one month later, in early May
425 2019 (Fig. 3d). The following subsidence lowered the pit-crater floor of about 90 m (Figs. 3d & 4c),

426 a value that can be explained by our model as it corresponds to the drainage of almost all the
427 melted layers interspersed in the pit crater (Fig. 5c).

428 Ground observations suggest that the central part of the pit crater has sunk as a single solid block
429 (as a piston), a feature that makes this subsidence episode similar to a caldera collapse. Moreover,
430 the time delay between the observed deformation and subsidence is reminiscent of caldera
431 collapses where faulting can precede subsidence by several days to weeks (Derrien et al., 2020;
432 Shelly and Thelen, 2019).

433 Caldera collapses, with subsequent resurgence of domes, share similar characteristics with those
434 modeled here (Smith and Bailey, 1968): (i) Nyamulagira follows a piston model with a solid block
435 of plane-like and of sub-circular shape, where subsidence begins when gravity exceeds the
436 frictional forces with the surrounding wall rock (Duputel and Rivera, 2019; Kumagai, 2001; Michon
437 et al., 2011); (ii) fracturing of the subsiding blocks has been observed to depend on the ratio block's
438 thickness (T) to diameter (D) - in our case we estimate $T/D=0.35$, which tends to favor sagging as
439 a single central block subsidence (piston) style with well-defined ring faults, which would not be the
440 case for much thinner crust (for which $T/D<0.3$) (Holohan et al., 2013, 2011; Roche et al., 2000).
441 With such a thickness (160 m, Fig. 5c), the underlying magmatic column remains confined beneath
442 the crust, except for intrusions around the block, which was actually observed (panel July 27, 2019
443 in Figure S5B); (iii) uplift of a solid block is favored by a crystallized front, which serves as a
444 rheological barrier whereby magma intrusions accumulate and exerts an upward pressure (Galetto
445 et al., 2017); (iv) any subsequent increase in magma volume potentially causes surface volcanism
446 concomitantly with the uplift of the emergent block (or injection of magma into fracture systems);
447 (v) low-viscosity magma would tend to dissipate magma pressure adjacent to the emergent block
448 with consequent surface volcanism.

449 Besides the involved spatial scale much smaller than in caldera forming volcanic settings, two main
450 differences can be highlighted: (1) subsidence is linked to the drainage of molten layers (Fig. 5c) in
451 addition to the piston effect, which could accelerate subsidence; (2) uplift of the solid block occurred
452 at a faster and constant rate of cm/hour instead of cm/year (Dvorak and Dzurisin, 1997; Geist et
453 al., 2006; Métrich et al., 2011; Ukawa et al., 2006).

454 The uplift of the solid block formed by the compaction of the remaining solidified layers (Fig. 5c),
455 which are lighter and cooler than the hottest and least differentiated magma (Sparks and Huppert,
456 1984), could be favored by an increase of the magma flow, and thus upward pressure. Taking the
457 hydrostatic pressure ρgH , where ρ and H are, respectively, the density and thickness of the solid
458 block (Fig. 5c), and taking into account the friction force against the cliffs (equation 4), then about
459 7 MPa are required to make it resurface (the hydrostatic pressure counting for 60%). This
460 represents an upper bound as most likely molten lava was interposed between the cliffs and the
461 block (which explains the lava flows on the edge of the crater floor, e.g. Fig. 4), thereby reducing
462 the frictional forces. The uplift of the solid block started in mid-July 2019 and was again
463 accompanied by LP earthquake swarms at depth similar to those recorded in May 2019.
464 Concomitant to the block uplift, fresh lavas flooded the area around it and finally overflowed the
465 caldera floor in February 2020 (Fig. 4e and injection along the margins of the solidified surfaces on
466 Supp. Fig. S5b).

467 According to Fig. 5c, there are no more interspaced molten layers and the whole piston is in contact
468 with the magma column.

469 **7.2 Towards an unconventional model of pit crater filling**

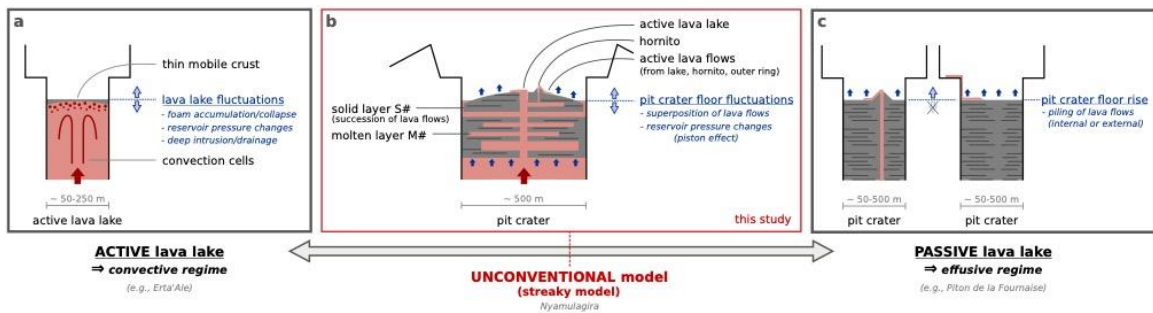
470 The thermal model reveals a filling mechanism of the pit crater by successive solid and liquid layers
471 whose thickness depends on frequency and size of the lava flows and size of the pit crater. This

472 filling pattern characterize the inactive lava lakes and is unconventional in the sense that it can be
473 defined as alternative to both (1) a purely convective mode, where the convection disrupts solid
474 layers (active lava lake, yellow zone on Fig. 2d) and (2) an effusive mode, where single flow units
475 have time to solidify before stacking up (blue zone on Fig. 2d). This unconventional mode, which
476 we call "streaky", is represented schematically in Fig. 6. Our model further highlights a filling
477 mechanism that could occur in other craters. For example the neighboring Nyiragongo volcano,
478 whose crater has been filled both by overflows of the lava lake (which also occupies only a portion
479 of its floor surface) and by intra-crateric eruptions that began in 2016 with the formation of a new
480 spatter cone (Burgi et al., 2020, 2018), shows great similitudes with Nyamulagira. However, no
481 similar subsidence or block uplift has been observed, probably due to the different physical
482 configuration of the crater and the underlying convective magma column.

483 Thermal models of discrete emplacement units of magma have previously been proposed to
484 explain the formation of magma reservoirs and plutons (Annen, 2011; Annen and Sparks, 2002;
485 Biggs and Annen, 2019; Blundy and Annen, 2016; Jackson et al., 2018; Michaut and Jaupart, 2011;
486 Sparks et al., 2019). A common feature of these models is the magma emplacement modality,
487 assumed to occur piecemeal with small increments rather than in a single large event. However,
488 these thermal models are based on the following assumptions that are not applicable in our case:
489 (i) successive magma injection through sills occurring upwards and downwards (Annen, 2011); (ii)
490 the layers being intruded are not subject to radiative heat loss and cooling is mainly done by
491 conductive loss; (iii) thick magma bodies may develop convective instabilities which accelerate
492 cooling (Simakin and Trubitsyn, 1995); (iv) timescales are tens to hundreds of thousands of years,
493 and spatial dimensions range on kilometer scale.

494 Solidification of lava lakes (Colp, 1982; Helz et al., 2014; Worster et al., 1993; Wright et al., 1976;
495 Wright and Marsh, 2016), which starts once the magma influx needed to keep the molten state

496 strongly decreases or ceases, represents another situation governed by thermal equations similar
 497 to those applied in our model. However, in the case of lava lake, the solidified surface crust
 498 preventing further radiative heat loss and cooling is mainly controlled by heat transfer by conduction
 499 to the host rocks, and through the upper crust of the lake to the air, corresponding to $\epsilon=0$ in equation
 500 (10). For stagnant lava ponds, such as the Kilauea inactive lava lakes (Wright et al., 1976), lava is
 501 accumulated through successive eruptive phases. Also, crust solidification is much slower in lava
 502 ponds than in our case: more than 7 years to solidify 80 m against less than 6 months in our case
 503 (Helz et al., 2014; Wright et al., 1976). A common feature though is the density profile with depth,
 504 where the cooled crust is lighter than the underlying hot melt.



505

506 **Fig. 6.** Conceptual models used to explain depth variations of pit-craters. (a) Active lava lake model,
 507 whereby the pit-crater hosts an active lava lake with convective cells: depth variations are
 508 commonly explained by foam accumulation/collapse beneath a thin solid crust, and/or pressure
 509 changes in the magma column/reservoir ("piston-effect"), and/or deep intrusion and magma column
 510 drainage (Patrick et al., 2019). (b) Unconventional "streaky" model presented in this study, whereby
 511 the pit-crater is filled by interleaved solid and molten layers: the depth fluctuations are explained by
 512 both the piling of lava flows, and by variations of the magma column/reservoir pressure. (c) Passive
 513 lava lake, whereby the pit-crater is filled passively by piling of lava flows from vents located inside

514 and/or outside the pit: the pit-crater floor does not fluctuate up/down, but only rises depending on
515 the effusive activity alone.

516 **4 Conclusions**

517 This case study, based on field and satellite measurements, and numerical modelling, shows a new
518 crater filling dynamic: while being in close contact with a magma column, Nyamulagira's pit crater
519 fills up incrementally by the overlapping of intra-crateric lava flows. This mechanism results in the
520 formation of solidified layers, interspersed with partially molten flow units, whose characteristics
521 depend on the temporal spacing between each emission of lava. Such an incremental filling of the
522 crater creates the conditions for the unconventional collapse and buoyant ascent of the solidified
523 layers, both of which constitute novel processes within pit craters. Our model thus contributes to
524 extend and improve our knowledge on processes underlying the dynamics of pit craters containing
525 lava lakes.

526 While the volcanic phenomena reported here are confined to the caldera, the underlying pressure
527 variations of the magmatic reservoir should be acknowledged as serious hazard for the region's
528 continuous population growth in the most western side of the Virunga Volcanic Province. Indeed,
529 lava flows generated by Nyamulagira directly threaten the city of Sake with a population of over
530 100,000 inhabitants (located 25 km from the volcano), and potentially lead to severe logistical
531 supply problems by cutting the only road that links Goma (the capital of North Kivu, population >1
532 million, located at about 30 km south east of the volcano) to the western and southern territories of
533 north and south Kivu (Balagizi et al., 2018; Patrick et al., 2019; Tedesco et al., 2007), as shown by
534 the recent event of the nearby Nyiragongo in May 2021.

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550

551 **Code and Data Availability**

552 All data generated or analyzed during this study are provided with this article, and are available at
553 <https://doi.org/10.26037/yareta:khivh7h2prgvxauarlckdo7awi>

554 MIROVA data, and the associated codes for computing the thickness and time of occurrence of the
555 lava flows, as well as thermal evolution of the lava layers are available at
556 <https://doi.org/10.26037/yareta:5futgivyездw5gdqqfogybt3ky>

557 Sentinel-1 and Sentinel-2 data used in this study are available and freely downloadable from the
558 Copernicus Open Access Hub (<https://scihub.copernicus.eu/>).

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